The Influence of Oxygen Additions on Argon-Shielded Gas Metal Arc Welding Processes

Mass flow, electric potential and temperature in the arc column were found to be little affected by additions of 5% or less oxygen.

ABSTRACT. It has been observed experimentally that small additions of oxygen to the argon shielding gas affect the general operation of GMAW processes. By theoretically modeling the arc column, it is shown that the addition of 2 to 5% oxygen to argon has an insignificant effect on the arc characteristics. This corresponds to the minor changes in the thermophysical transport and thermodynamic properties caused by the oxygen addition. Therefore, it is concluded that the addition of oxygen to the argon shielding gas mainly affects the anode and the cathode regions. From the literature, it was found that the formation of oxides initiates arcing at the cathode and decreases the movement of the cathode spots. These oxides can also improve the wetting conditions at the workpiece and the electrode. Finally, oxygen is found to affect the surface tension gradient and thereby the convective flow of liquid metal in the weld pool.

Introduction

In the early fifties, it was found that the addition of small amounts of oxygen to the argon shielding gas in gas metal arc welding (GMAW) allowed the range of weldable materials to be extended from aluminum and stainless steel to include carbon steels (Ref. 1). Today, oxygen additions to the shielding gas are widely used in many applications of the GMAW process. It is commonly believed that oxygen reduces the surface tension of the metal and improves the arc stability and arc root behavior. So far, no information has been published in the open literature regarding the effects of oxygen additions on the characteristics of the arc column. The main reasons for this have been the difficulty in obtaining high-temperature data for thermophysical properties for an argon-oxygen mixture, and the lack of a gas metal arc model. However, recent developments at CSIRO have increased the reliability of calculations of the thermophysical properties for a large number of gas mixtures. Also, some recent work in our laboratory at MIT has led to the development of the first model representing the gas metal arc.

The main purpose of this article is to present the results of our study of the effects of oxygen addition on the characteristics of an argon arc for GMAW of iron and aluminum. We shall also relate these findings to previous studies of the importance of oxygen in the anode and cathode region, in order to give a more complete description of the influence of oxygen additions on the performance of the GMAW process.

One section of the article describes the GMAW process, and another section summarizes previous work on the influence of oxygen addition on arc welding processes. We then describe the method of calculation of the thermophysical properties and the calculation of the arc characteristics. Finally, by examining our calculated results in conjunction with previously reported work, we discuss the influence of oxygen additions on argon-shielded GMAW processes.

Background

Figure 1 shows the main components of the GMAW system, which is seen to consist of the consumable electrode (anode), the anode-fall region, the arc column, the cathode-fall region and the workpiece (cathode). The figure also includes the gas-shielding nozzle, through which the shielding gas is supplied to the arc.

When an arc is struck between the...
anode and the cathode, a current flows through the electric discharge between the electrodes. The arc current is spread laterally and a jet is formed which gives rise to a flow in the direction of the cathode (workpiece). The gas impinges on the workpiece and is spread in a direction parallel to the workpiece. Also, the current distribution at the anode gives rise to a high heat generation in the near anode area, which results in a rapid melting of the consumable electrode. Droplets are formed at the melted tip, detached from the electrode, and are transferred to the workpiece under the influence of arc forces. The melted droplets solidify at the workpiece and form the welded joint.

Of the two workpiece materials discussed in this article, aluminum is known to be a nonthermionic cathode characterized by a mobile cathode spot (Ref. 2). It is not clear, on the other hand, whether thermionic or nonthermionic emission of electrons occurs from iron cathodes (Ref. 3). However, the following observations indicate that iron shows more of a nonthermionic than a thermionic cathode behavior. First, Essers and Walter (Ref. 4) found that the calculated value of the current density, as a result of thermionic emission, is very low. Second, the mobile cathode spot behavior usually observed for nonthermionic cathodes is also observed in GMAW of steel (Ref. 3). Third, calculated values of the current density, as a result of thermionic emission, have shown good agreement with experimental data on materials with boiling points of at least 4000 K (Ref. 3) (the boiling point of iron is 3343 K (Ref. 5)). Based on these findings, iron will be treated as a nonthermionic electron emitter in this study.

Previous Work

Initially, some general observations of the influence of oxygen on the GMAW process will be presented. Thereafter, the review of the importance of oxygen in GMAW operations will be separated into two main parts: 1) the effects due to oxide formation, and 2) the effects due to the influence on surface tension gradients of liquid metals. In doing this, we choose to include results from other arc welding processes for the sake of completeness.

In general, experimental observations have shown that oxygen additions to a shielding gas have a major impact on the weld pool, leading to an increased length, width, volume and section (Ref. 6). However, use of an oxidizing gas can cause some ferrous metals to become porous, and therefore reducing elements are usually added to the electrode to compensate for this effect (Ref. 7). Also, it has been found that addition of too high a proportion of oxygen, 7 to 8% or more, to the argon shielding gas increases slag formation and leads to firmer attachment of the slag to the surface (Ref. 8).

It has also been found that an improvement in the toughness of ferritic steels may be obtained by increasing the oxidizing potential through addition of up to 2% oxygen to the argon shielding gas (Ref. 9). Moreover, Francis, et al. (Ref. 10), found that the use of an argon-based gas with 2 to 4% oxygen and the composition of the welding wire, are critical in achieving a high fracture toughness. According to the authors, the fracture toughness is determined by the amount of acicular ferrite formed, which is dependent on the number and size of oxide inclusions.

Effects Due to Oxide Formation

It is commonly believed that nonthermionic cathodes operate by the continuous formation and decay of several small electron-emitting sites (cathode spots, Refs. 3, 11). The site lifetime for thick oxide films on mild steel has been shown to be as low as 1 ns (Ref. 12). The oxides, formed by reactions between oxygen and workpiece elements, are believed to act as a source of electrons, because they usually have a lower work function than the metal (Ref. 13). The oxides are also thought to be charged by incident positive ions and to emit electrons by a tunneling mechanism and a switching mechanism for oxide thicknesses smaller than 5 nm and larger than 10 nm, respectively (Ref. 14). For welding arcs acting on an oxidized steel piece, each emitting site has been found to carry up to 1 A of current (Ref. 15). The emitting sites are also said to move outward toward fresh oxide and to consume it at a certain rate (Ref. 16). The area over which the oxide is removed increases with an increase in the change in the cathode voltage drop (Ref. 17).

The mobility of nonthermionic cathode spots is undesirable in GMAW, be-
cause it causes arc instabilities, which makes welding more difficult (Ref. 15). For the case of an aluminum workpiece material, it has been shown that the presence of a relatively thick oxide layer tends to restrict the mobility of the cathode spot (Ref. 2). According to Lancaster (Ref. 2), the thickness of the metal oxide increases if oxygen is added to an argon shielding gas. He used this reasoning to explain the observation of a lower mobility of the electron emitting sites for GMAW of steel when small amounts of oxygen were added to the argon shielding gas.

Oxides, in the form of nonmetallic inclusions formed by reactions between oxygen and alloying elements, have also been shown to affect the cathode behavior. Hancox (Ref. 18) found that the arc could not be struck between two very pure iron electrodes if oxygen was removed from the argon gas. The use of very pure argon gas has also been shown to result in unstable metal transfer during GMAW of aluminum (Ref. 21).

Oxygen additions are also known to promote the wetting of the workpiece by the weld pool (wetting-in of the weld pool) (Ref. 22). In general, good wetting conditions are achieved if the contact angle, defined in Fig. 2, is low. Bradstreet (Ref. 23) found that when oxygen was present in the shielding gas, the value of this contact angle decreased due to the presence of a film of SiO₂ on the molten steel. It was believed that silica acted as a wetting agent, due to the low value of its surface tension (0.2 to 0.26 Nm⁻¹, Ref. 23) compared to that of steel (1.7 to 1.9 Nm⁻¹, Refs. 24, 25), and thereby improved the wetting conditions.

**Effects Due to Influence on Surface Tension of Liquid Metal**

Surface tension gradients, dy/dT, where ρ is the surface tension of the liquid metal and T is the temperature, are known to give rise to thermocapillary (Marangoni) convection, cause high surface velocities, and play a major role in determining the surface-tension-driven flow in weld pools (Ref. 26). In early theoretical investigations of weld pools, in which the value of dy/dT was assumed to be constant, it was found that the surface-tension-driven flow had a profound effect on the weld pool shape both in GMAW (Refs. 27–29) and in gas tungsten arc welding (GTAW) systems (Refs. 30–36).

The assumption that the value of the surface tension gradient was constant, which was made due to the lack of experimental or theoretical data for dy/dT, was a serious limitation, since Heiple and Roper (Ref. 37) proposed that surface-active elements could actually change the sign of the surface tension gradient, and thereby the direction of the flow.

The first semi-empirical theoretical relationship between the surface tension gradient and the temperature and activity of the surface-active element was derived from Gibbs and Langmuir isotherms by Sahoo, et al. (Ref. 38).

If oxygen is taken as the surface-active element, the surface tension gradient can be expressed as

$$\frac{dy}{dT} = -A - R\gamma_0 \ln(1 + K_{seg} a_0) - \frac{K_{seg} \gamma_0}{(1 + K_{seg} a_0) T}$$

where A is a constant in the surface tension coefficient, R is the gas constant, η is the surface excess at saturation, a₀ is the activity of oxygen, and ΔH₄ is the standard heat of adsorption.

The surface tension gradient is negative for most pure metals and the corresponding surface-tension-driven flow in the weld pool is directed towards the edges of the weld pool as shown in Fig. 3A. The addition of oxygen to an iron melt can change the sign of the surface tension gradient to positive (Ref. 38). This will change the corresponding flow pattern in the weld pool so that the surface velocities are directed toward the center of the weld pool, as illustrated in Fig. 3B.

Recent mathematical models of the GTAW system by Zacharia, et al. (Refs. 39–42), used Equation 1 to predict the influence of surface-active elements and temperature distribution on the weld pool geometry. It was quantitatively
Theoretical Modeling

Calculation of Thermophysical Gas Properties

The model of the arc column that we use requires values of the density, enthalpy, specific heat, viscosity, thermal conductivity, and radiative emission coefficients as a function of temperature for pure argon and mixtures of argon and oxygen. The radiation loss terms for both argon and the argon-oxygen mixtures are taken from experimental data for argon of Evans and Tankin (Ref. 43). The radiation loss terms for the argon-oxygen mixtures are assumed to be the same as for argon, because the total radiation of oxygen is of the same order of magnitude as for argon (Ref. 44) and only 2 to 5% oxygen is added. The other quantities are calculated using a code designed to calculate the equilibrium compositions and thermophysical properties of nonionized gas mixtures (Refs. 45, 46), which has been modified by Kovitya (Refs. 47–49) to allow for treatment of ionized gases.

All calculations are performed assuming local thermodynamic equilibrium. The initial step in the determination of the thermophysical properties is the calculation of the equilibrium composition of the gas or gas mixture, which is done using the principle of minimization of the Gibbs free energy. The species considered are Ar, Ar++, Ar++, O2, O2+, O+, O++, O++, and the electron. The presence of metallic species is neglected, since the focus is on studying the effect of oxygen additions on the argon plasma. The required partition functions for the considered species are calculated from the data tabulated by Moore (Ref. 50) for neutral and positively charged monoatomic species, and from data given in the JANAF tables (Ref. 51) for other species. The Debye-Hückel correction is applied, as described by Kovitya (Ref. 49).

The density of the mixture at temperature T and pressure P is calculated using

$$\rho = \frac{P}{RT} \sum x_j M_j$$

where xₖ is the mole fraction and Mⱼ is the molecular weight of the jth species. The enthalpy and specific heat of the mixture are calculated using the expressions given by Kovitya (Ref. 49), which includes terms for the Debye-Hückel correction.

The transport coefficients; viscosity, thermal conductivity, and electrical conductivity; are calculated using the Chapman-Enskog method (Refs. 52–54). Details of the calculations are given by Murphy (Ref. 55). The thermal conductivity is calculated as the sum of the contributions due to the translational, internal, and reaction components. The translational component is further broken down into contributions due to heavy particle and electron motion; the electron component is calculated to a third level of approximation, while the heavy particle component is calculated to a second level. Note that the first level of approximation for the thermal conductivity is identically zero. The electrical conductivity is calculated to a third level of approximation, neglecting the influence of ion transport. The viscosity is calculated to a first level of approximation.
Devoto (Refs. 56, 57) has verified that the levels of approximation used give results accurate to within 1% for argon, except for the electrical conductivity at very low levels of ionization. Since the electrical conductivity is very low under these conditions, the absolute error is always small (less than 200 S/m).

The collision integrals, integrals over a Maxwellian distribution of the collision cross-sections for interactions between the various species, are required to calculate the transport coefficients. Most of the integrals are calculated from the intermolecular potentials given by Auberton, et al. (Ref. 58). However, in a number of cases improved data are used. The collision integrals for the Ar-Ar and Ar-O₂ interactions are respectively calculated from the HFDTCS2 potential given by Aziz and Slaman (Ref. 59) and the ESMSV potential given by Pirani and Vecchiocattivi (Ref. 60). The charge-exchange cross-section required in the calculation of the collision integrals for the O-O interaction is taken from the experimental results of Rutherford and Vroom (Ref. 61).

The collision integral tabulations of Levin, et al. (Ref. 62), and Stallcop, et al. (Ref. 63), are used directly for the O-O and O⁺-O interactions respectively. Finally, the collision integrals for electron-neutral interactions are treated by numerical integration of the momentum-transfer cross-section data presented by Itikawa (Refs. 64, 65), supplemented at low and high energies by further data from Itikawa's sources.

Our values for the thermodynamic properties of argon and argon-oxygen mixtures are expected to be considerably more reliable than less-recent values (Ref. 55). This, and the small concentrations of oxygen considered in the calculations, means that our transport properties of argon-oxygen mixtures will not be significantly less accurate than our results for pure argon.

The calculated thermophysical properties for the shielding gases considered in this paper are shown, and discussed later.

### Description of Arc Model

A two-dimensional steady-state mathematical model has been developed to predict properties such as temperature, velocity, and voltage in the gas metal arc. In an earlier study, the model was applied to GMAW of aluminum in an argon atmosphere (Ref. 66). Calculated values for temperatures, at an axial location halfway between the electrode and the workpiece, were found to differ by 0 to 6.1% and 0 to 3.8% in comparison with
The primary difference to the earlier model application to GMAW of aluminum (Ref. 66) is that the arc column is modeled under the assumption of local thermal equilibrium (LTE). In the earlier model application, non-LTE conditions in the cathode and anode fall regions were accounted for in a simplified way (through source terms in the plasma region close to the anode and the cathode). However, in this investigation the focus is on the majority of the plasma region where LTE exists and not on the small non-LTE boundary layer regions (< 0.1 mm (Ref. 68)). Therefore, we neglect the simplified approach to account for non-LTE boundary regions that was used in the earlier study (Ref. 66).

The paragraphs below summarize the key assumptions, equations, and boundary conditions used in the model. A more detailed description of the mathematical model can be found in an earlier publication (Ref. 66).

**Mathematical Formulation**

The boundaries of the computational domain for the welding arc are shown in Fig. 4. The system is assumed to be axisymmetric, steady-state and laminar. The plasma is assumed to be at atmospheric pressure, in local thermodynamic equilibrium, optically thin to radiation and the influence of metal droplets is neglected. Also, the consumable electrode is assumed to be cylindrical, and the tip of the electrode and the workpiece surfaces are assumed to be flat.

In applying the above assumptions, the equations, written in cylindrical coordinates, that need to be solved are the conservation of mass, radial and axial momentum, thermal energy, and charge continuity (expressed in the form of the electrical potential). The definitions of the electric potential and Ampere's law are used to calculate the current densities and the self-induced magnetic field, respectively.

The boundary conditions for the welding arc are listed in Table 1 and the variables used in Table 1 are defined in the Appendix. In the anode region (BC, CD in Fig. 4), a no-slip condition is used for the momentum boundary conditions. The enthalpy at the anode $h_a$ is set to the value corresponding to the melting temperature of pure iron (1810 K) or pure aluminum (933 K). The equation for the conservation of charge continuity is the only equation to be solved within the electrode region, and therefore, the potential is set to be constant in region DA — Fig. 4. In the region DE, a zero mass-flow gradient $dpw/dz$ was postulated, together with an inlet enthalpy $h_i$ corresponding to a temperature of 300 K. Since it is not clear where inflow (EF) and outflow (FG) will take place in the fringes of the arc column, zero radial mass flow $dpw/dr$ and electric potential gradients were specified. The enthalpy is assumed to correspond to a temperature of 300 K for the gas en-
trained into the system and the enthalpy gradient dh/dr is assumed to be zero for mass flowing out of the system.

In the cathode region (GHI), a no-slip condition is used for the momentum equations. The enthalpies at the cathode surface within h₁₀ and outside h₀, the weld pool (cathode spot) region are taken at temperature values of 1810 and 1000 K for iron and 933 and 600 K for aluminum, respectively. The radius of the cathode spot Rc is defined as an average value representing the movement of the cathode spot. Theoretical calculations of the weld pool profiles showed that the weld pool radius in argon shielded systems is 3.2 to 3.5 mm (0.125 and 0.138 in.) for welding currents of 150 to 220 A (Ref. 27, 28). Based on these values of the weld pool radius, a sensitivity calculation was done to study the effect of the cathode spot radius on the calculated arc characteristics. It was found that the calculated maximum velocity varies less than 1.7% and the maximum temperature varies less than 0.1% for a 2.7 to 4.2 mm (0.11-0.16 in.) range of the cathode spot radius. Therefore, Rc was chosen to be 2.7 mm.

It is assumed that a single value of the current density Jc is valid within the cathode spot (weld pool) region and that the current density is zero outside the cathode spot region. This assumption is based on the strong dependence of the current density on surface temperature; the temperatures in the weld pool region are substantially higher than in the rest of the workpiece. Therefore, the current density conditions at the cathode are given by:

\[ J_c = \frac{1}{\pi R_c^2} \quad r \leq R_c \]  

The influence of oxygen on phenomena taking place at the workpiece (cathode).

**Method of Solution**

The solution of the governing equations and boundary conditions is obtained by using a modified version of 2/E/FIX, a two-dimensional steady-state code based on a finite volume scheme (Ref. 69). During a calculation, the difference equations are solved by iteration until the residuals are less than 1% of the magnitude of the respective variables. The current balance is satisfied within 1% for all calculations.

Theoretical inputs in the form of thermophysical gas properties are calculated as described earlier. The values of the electrical conductivity of iron and aluminum at their respective melting points are taken from Touloukian (Ref. 70).

**Results**

Our calculations were done for GMAW of aluminum and iron using the following shielding gases: 1) pure argon; 2) 98% argon - 2% oxygen; and 3) 95% argon - 5% oxygen by weight. The studied range of currents, the arc length and the electrode diameter were 150 to 400 A, 10.0 and 1.2 mm, respectively.

**Thermophysical Gas Properties**

As mentioned earlier, the thermodynamic and transport properties of the shielding gases were calculated using the program developed at CSIRO (Ref. 47). Figures 5 to 7 show the enthalpy, density, and specific heat as a function of temperature. It is obvious from the figures that the addition of oxygen has an insignificant effect on the density, and only small effect on the enthalpy and the specific heat. The largest enthalpy differences occur in the temperature range of 2500 to 12000 K, for which oxygen additions tend to increase the value of the enthalpy slightly. The most noticeable effect of oxygen additions on the specific heat is found at a temperature of 3000 K, where a peak value is found, corresponding to the dissociation of oxygen molecules.

The transport properties; electrical conductivity, thermal conductivity and molecular viscosity; are plotted vs. temperature in Figs. 8-10, respectively. The electrical conductivity is found to increase slightly with increased oxygen...
The assumptions that are made in the arc model mean that the different anode and cathode materials only influence the arc characteristics through the temperature boundary conditions. More specifically, the different melting temperatures of iron (1810 K) and aluminum (933 K) was the only difference in the models of the iron and aluminum systems. The calculated arc characteristics were found to be independent of this difference in melting temperature. A similar finding has been reported for temperature measurements in the GTA welding system; the use of iron or water-cooled copper anodes did not affect the measured temperature profiles (Refs. 71, 72). Our present results for the characteristics of the arc column are thus valid for both GMAW of iron and aluminum.

The maximum value of the mass flow (pu) is shown as a function of welding current in Fig. 11. It can be seen that an addition of 5% oxygen to the argon shielding gas decreases the mass flow by between 1.4 and 2.6%. The maximum value of the momentum flux (u^2) is plotted vs. the welding current in Fig. 12. A 95% argon - 5% oxygen gas mixture is found to result in a slightly higher momentum flux, by between 1.3 and 3.4%, in comparison with pure argon. In Fig. 13, the maximum value of the electric potential is shown as a function of the welding current. The addition of 5% oxygen to argon gas increases the value of the electric potential by between 2.8 and 5.1%.

The axial velocity, at the center of the arc and a 250 A welding current, is plotted vs. the axial distance, taken from the anode to the cathode, in Fig. 14. A relatively uniform velocity is found in the arc column, while the velocity decreases dramatically close to the solid anode and cathode surfaces. The addition of 5% oxygen to the argon gas increases the velocity by up to 9.4%. Similarly to Fig. 14, the temperature is plotted vs. the axial distance for a 250 A welding current in Fig. 15. The highest temperatures are found near the anode, where the rate of joule heat generation is highest. The addition of 5% oxygen to the argon gas is found to increase the temperature by a maximum of only 3.8%. Finally, the electric field intensity is shown as a function of axial distance for a 250 A welding current in Fig. 16. The absolute value of the electric field is about 0.8 to 1.0 V mm^-1 at a location halfway between the anode and the cathode, while it increases in magnitude closer to the anode and the cathode. The addition of 5% oxygen to the argon gas is found to decrease the magnitude of the electric field intensity by up to 5%.

**Comparison of Predicted Arc Characteristics and Experimental Data**

As mentioned previously, the predicted arc characteristics were in good agreement with spectroscopically measured temperatures. Besides temperatures, it is also important to compare data of the electrical characteristics, especially since Eager (Ref. 73) has shown that the majority of the energy transferred to the anode from the welding arc is carried by the current. Such a comparison has recently been done by Jonsson, et al. (Ref. 74). However, in this paper, predicted electrical characteristics presented are compared with data from the literature.

The electric potential in the arc column for a pure argon arc is shown to be approximately 13 V at a 200 A welding current — Fig. 13. Adding a voltage drop of 14.9 V for the anode and cathode fall regions (Ref. 21) and 5% argon to argon gas, gives a total voltage of about 28 V. This is reasonably close to the value of the total voltage of 25 V at a 200 A welding current (data of arc length and electrode diameter are unknown) given by Jackson (Ref. 75). From Fig. 16 it is seen that the absolute value of the predicted electric field intensity is 0.8 to 1.0 V mm^-1 in the center of the arc. These values agree well with the average values of the electric field intensity of 0.7 to 0.8 V mm^-1 reported by Allum (Ref. 76). In that study it was also shown that the electric field intensity increases to 2.5 V mm^-1 at a distance of 1 mm (0.04 in.) from the cathode. This tendency for the electric field intensity to increase as the cathode is approached is also seen in Fig. 16. However, it should be noted that the accuracy of the predicted values decreases at locations close to the cathode (and the anode), since the influence of the non-LTE cathode fall boundary layer is neglected in the model. As indicated in a recent survey of theoretical welding models (Ref. 77), the theoretical treatment of these non-LTE regions is far from perfected. So far, even the most comprehensive studies modeling the cathode and anode fall regions have used one-dimensional approaches, and they have all been for the related and more studied gas tungsten arc.

**Discussion**

In the literature review, it was mentioned that it is difficult to strike an arc in a pure argon atmosphere (Ref. 20) and that unstable metal transfer is often observed in these arcs (Ref. 21). The addition of oxygen to the argon shielding gas generally improves the ability to strike an arc and maintain a more stable metal transfer. Up till now, it has not been clear if this is due to effects on the arc characteristics or phenomena at the anode and cathode.

The results shown in Figs. 11–16 indicate that the addition of oxygen to the argon shielding gas has only a small influence on the characteristics of the arc column. The small magnitude of the effect can primarily be explained by the small effect of oxygen additions on the transport and thermodynamic properties of argon, as shown in Figs. 5–10. The absence of major changes to the predicted arc column characteristics indicates that the observed effects of the addition of oxygen to an argon-shielded GMAW process are mainly due to altered transport phenomena at the anode and the cathode. Therefore, it is important to know how much oxygen is added to the arc and how it affects the arc characteristics at the anode and the cathode.

**Cathode — Workpiece (Weld Pool)**

From the literature review, it is clear that the influence of oxygen on the transport phenomena taking place at the cathode has been studied quite extensively. The most important influences of oxygen additions upon phenomena that take place at the workpiece are summarized in Fig. 17. It is seen that the addition of oxygen leads to improved arc stability by: 1) forming nonmetallic inclusions that initiate arcing; and 2) by forming oxides that decrease the movement of the arc (cathode spots). Oxygen also affects the geometry of the weldment by: 1) forming films that improve the wetting conditions of the weld pool; and 2) by affecting the surface tension gradient such that deeper and more narrow weld pools are formed.
Anode — Consumable Electrode

Considerably fewer publications have discussed the influence of oxygen on phenomena taking place at the consumable electrode (anode) than at the cathode. Kim (Ref. 13) studied the melting characteristics of GMAW of iron using pure argon and argon with the addition of 2% oxygen as shielding gases. He found that the presence of oxygen did not affect the melting rate significantly. Similarly, Freeman and Eagar (Ref. 78) studied the same welding system and shielding gases. They found no difference in drop frequency for the pure argon gas and the 98% argon - 2% oxygen mixture. However, they noticed that the average drop size and neck diameter were smaller for the case using pure argon as a shielding gas. Furthermore, the droplets in the pure argon system were more elongated, resembling an elliptical shape. Questioning any assumption that can be made from these results that the addition of oxygen does lead to a larger droplet size, are the results from a further study by Jönsson (Ref. 79). He found that the droplet diameter for a 95% argon - 5% carbon dioxide shielding gas mixture was smaller (and the frequency of the droplets is higher) than for a 98% argon - 2% oxygen shielding gas mixture at all currents, as is illustrated in Fig. 18.

The 95% argon - 5% carbon dioxide shielding gas mixture contains a higher oxygen content than the 98% argon - 2% oxygen mixture. Oxygen from the shielding gas can dissolve in the liquid iron as a result of chemical reaction between the gas phase and the liquid iron droplet. The surface tension of liquid iron decreases with an increased oxygen concentration (Ref. 80). Therefore, it is expected that the "oxygen richer" 95% argon - 5% carbon dioxide gas mixture lowers the surface tension more than the 98% argon - 2% oxygen mixture. The effect of surface tension on droplet detachment can be estimated using the static force balance theory (Refs. 13, 81, 82). This states that a droplet detaches from the electrode tip when the static detaching forces (gravitational, electromagnetic and plasma drag forces) exceed the static retaining force due to surface tension. Thus, the observation of smaller droplet sizes and higher droplet frequencies for the argon - carbon dioxide mixture compared to the argon - oxygen mixture in Fig. 18, is explained by the lower value of the surface tension and thereby the lower surface tension retaining force for the argon - carbon dioxide shielding gas.

In summary, the different experimental results reported regarding the influence of oxygen additions on transport phenomena at the anode indicate that a clear understanding of the phenomena involved does not exist. It is an important topic that needs to be investigated further.

Conclusions

The main conclusions of this study can be summarized as follows:

1) The addition of up to 5% oxygen to an argon shielding gas was found to affect the characteristics of the arc column to only a small extent. More specifically, the mass flow, momentum flux, electric potential and temperature were found to change by no more than 5% when oxygen was added to the argon gas.

2) It has been reported that the addition of oxygen to the argon shielding gas affects the general operation of a GMAW process. Since this study has shown that the effect is small in the arc column, it is concluded that the effects are taking place at the anode and cathode regions. The influence of oxygen on the transport phenomena taking place at the cathode has already been studied quite extensively, while more investigation is greatly needed on activity at the anode.

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References

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Appendix

Nomenclature

- $a_0$: Activity of oxygen (-)
- $A$: Constant in the surface tension coefficient (Nm$^{-1}$K$^{-1}$)
- $h$: Plasma enthalpy (Jkg$^{-1}$)
- $h_a$: Enthalpy at the anode (Jkg$^{-1}$)
- $h_i$: Enthalpy of gas flowing into the system (Jkg$^{-1}$)
- $h_{c,i}$: Enthalpy at the cathode surface within the cathode spot region (Jkg$^{-1}$)
- $h_{c,o}$: Enthalpy at the cathode surface outside the cathode spot region (Jkg$^{-1}$)
- $I$: Welding current (A)
- $I_c$: Cathode current density (Am$^{-2}$)
- $K_a$: Equilibrium constant for segregation (-)
- $M_i$: Molecular weight of the $i$th species (kgmol$^{-1}$)
- $P$: Pressure (Nm$^{-2}$)
- $r$: Radial distance (m)
- $R$: Gas constant (Jmol$^{-1}$K$^{-1}$)
- $R_c$: Cathode spot (weld pool) radius (m)
- $T$: Temperature (K)
- $u$: Radial velocity (ms$^{-1}$)
- $w$: Axial velocity (ms$^{-1}$)
- $x_j$: Mole fraction of the $j$th species (-)
- $z$: Axial distance (m)

Greek Symbols

- $\Delta H^\circ$: Standard heat of adsorption (Jmol$^{-1}$)
- $\rho$: Density (kgm$^{-3}$)
- $\Phi$: Electric potential (V)
- $\gamma$: Surface tension (Nm$^{-1}$)
- $\gamma_l$: Surface tension of liquid metal (Nm$^{-1}$)
- $\gamma_s$: Surface tension of solid metal (Nm$^{-1}$)
- $\gamma_{sl}$: Solid/liquid interfacial tension (Nm$^{-1}$)
- $\Gamma_0$: Surface excess at saturation (molm$^{-2}$)
- $\theta$: Wetting contact angle (degrees)

American Welding Society — 1995 Conferences

Golden Gate Materials Technology Conference, February 1-3, 1995, San Francisco, California. Concentration is given to areas such as the selection of materials for challenging performance and environmental applications; the production, inspection, and preservation of equipment and structures; and the development of technology to test and characterize materials improvements. Leading manufacturers will exhibit.


Sixth International Conference on Aluminum Weldments (INALCO '95), April 3-5, 1995, Cleveland, Ohio. This conference will be conducted concurrently with the AWS Annual Convention and Exposition. Topics will focus on design, fabrication, inspection and quality control of aluminum weldments, with special emphasis on design of weldments, tools for design, application examples, non-welding joining processes, behavior improvement, cast and extruded aluminum, inspection techniques and codes and standards.

1995 International Conference on Microbi ally Influenced Corrosion, May 8-10, 1995, New Orleans, Louisiana. Three broad areas are envisioned in the scope of this conference: biological aspects, materials including weldments, and corrosion. Topics include: theoretical, materials and welding considerations, case studies; monitoring technologies; biocides and treatment; economics; and regulatory considerations mechanisms. A mini-exposition will be held.

Aluminum Welding Seminar, October 5-6, 1995, Pittsburgh, Pennsylvania. Presentations include an introduction to aluminum joining; selection of aluminum alloys and characteristics; gas tungsten arc welding of aluminum; gas metal arc welding of aluminum; aluminum welding metallurgy; metal preparation for welding; welding discontinuities- causes and cures; plasma cutting and gouging; performance of aluminum welds; welding exposure studies; and laser cutting and welding. Leading manufacturers will exhibit.

Eleventh North American Welding Research Conference: Joining for the Automotive Industry, October 17-18, 1995, Southfield, Michigan. Tentative sessions titles include: design for welding; tailored blank manufacturing; alternative materials (plastics, adhesives, aluminum, magnesium); process control/NDT; resistance welding; alternative processes-weld bonding, power beams; welding automation; TQJ.

Watch for the following conferences to be scheduled for the fall of 1995:

- Welding of Stainless Steels and Nickel Alloys
- Structural Steel Applications

For further information, contact: Conferences, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126, 800-443-9353, Ext. 278, or 305-443-9353, Ext. 278, Fax: 305-443-6445.